R-197
35240.

UNPUBLISHED PRELIMINARY DATA

POLARIZERS FOR THE EXTREME ULTRAVIOLET*

W. R. Hunter
E. O. Hulburt Center for Space Research**
U. S. Naval Research Laboratory
Washington, D. C., 20390

Submitted for publication in

Japanese Journal of Applied Physics

*Supported, in party, by National Aeronautics and Space Administration.

**Sponsored jointly by Office of Naval Research and National Science Foundation.

(7140-PRR-26/64:WRH:geg--August 1964)

[redacted]

7140-PRR-26/64:WRH:geg

POLARIZERS FOR THE EXTREME ULTRAVIOLET*

W. R. Hunter
E. O. Hulburt Center for Space Research**
U. S. Naval Research Laboratory
Washington, D. C. 20390

33377

ABSTRACT

The polarizing properties of materials in the extreme ultraviolet are being studied for the purpose of developing both reflecting and transmitting polarizers. Calculations of the ratios $R_s/R_p = \rho$ and $T_p/T_s = 1/\rho$ have been made for some of those materials whose optical constants have been measured and an attempt was made to verify the calculated ratios experimentally where possible. The calculations indicate the possibility of making transmitting polarizers, using multilayer unbacked metal films, for wavelengths less than the critical wavelength of the metal. The calculated value of $1/\rho$ for Au/Al/Au at 640 Å and $i = 42^\circ$ was found to be 15, but T_p, for this multilayer film, is only a few percent. Reflecting polarizers, which are much less convenient to use, show more complete polarization. For example, for Au/Al/Glass at 640 Å, $\rho = 35$ at $i = 62^\circ$, and $R_s = 30\%$.

---

*Supported, in part, by National Aeronautics and Space Administration
**Sponsored jointly by Office of Naval Research and National Science Foundation

[redacted]

I. INTRODUCTION

The need for polarizers for the extreme ultraviolet (XUV) has been emphasized by some recent experimental work by Cardona [1], who has been able to observe features in the reflectance spectra of Wurtzite crystals that would not have been possible with unpolarized radiation. An interpretation of the reflectance maxima of such spectra has been made by J. C. Phillips [2] who found quite good agreement with theory. Phillips points out that a much better idea of the band structure of crystals is available from XUV reflectance spectra than can be obtained in the visible or near infrared, and that the interpretation of such spectra would be made easier if they could be measured using polarized radiation. This has not been possible thus far because of the inadequacies of conventional polarizers in the XUV and it is only recently since measurements of the optical constants have been undertaken, that polarizers for the XUV can be designed.

Polarized radiation can also be produced by sources, for example, the synchrotron, whose radiation has a high degree of polarization. These instruments are not accessible to most experimenters, hence they will not be discussed here.

II. METHODS OF PRODUCING POLARIZED RADIATION

1. Reflection

Polarization by reflection presents the most obvious method for obtaining polarized radiation in the XUV. The degree of polarization, given by $R_s/R_p = \rho$, can be calculated using the Generalized Fresnel Reflection Coefficients once the optical constants of the substance are known. This ratio is always greater than unity if no interference effects are present. The dependence of $\rho_{max.}$ and R_s on the optical constants has been calculated for certain values of n and k with the results shown in Fig. 1. The angle of incidence at which $\rho_{max.}$ occurs ranges from 9^o to 66^o for k = 0.1, 34^o to 67^o for k = 0.5, and from 57^o to 70^o for k = 1.3, while the width of the peaks of $\rho_{max.}$ at half value may be 10^o or more. It is apparent that the larger the ratio of n/k, the more effective the substance is as a polarizer, however, large values of $\rho_{max.}$ do not necessarily ensure large values for R_s as the lower portion of the figure shows. For n = 1.0, and k = 0.1, R_s reaches a minimum value of approximately 0.9% while $\rho_{max.}$ = 100. The proportionality between n/k and $\rho_{max.}$ is not unexpected; for the extreme case of a pure dielectric, the ratio n/k is infinite and at Brewster's angle, $\rho_{max.}$ is also infinite. This behavior has been pointed out by Sasaki and Fukutani (3) who have shown by calculation that $\rho_{max.}$ occurs approximately at the Brewster angle for small k. At the other extreme, for small n/k, the reflectance is high and since both R_s and R_p are large, $\rho_{max.}$ is approximately unity.

Dielectrics meet the condition required for maximum polarization; that is, large n/k, and a number of them are transparent in the XUV. LiF, for example, is transparent to wavelengths as short as 1050 Å, while other alkali halides cut off at somewhat longer wavelengths. Al_2O_3 and MgF_2 are also transparent in the XUV. Thus, in principle, polarization by reflection can be easily accomplished to wavelengths as short as 1050 Å. Cardona [1] has employed a LiF reflector, held approximately at the Brewster angle, between the light source and the entrance slit of a monochromator, to produce polarized radiation. He estimated that the polarization was practically complete because in the reflectance spectra of crystals, certain features were absent that would have been observed had the polarization been less than 100%.

For wavelengths shorter than 1050 Å, there are no known materials for which $k = 0$, consequently the large values of polarization that occur with dielectrics cannot be realized in this spectral region. A calculation of $\rho_{max.}$ and R_s for glass, evaporated films of Au, ZnS and anodically formed films of Al_2O_3 are shown in Fig. 2. Au has the most uniform polarization characteristics; $\rho_{max.}$ varies between 5 and 7 from 600 Å to 2000 Å, while below 600 Å, the fluctuations in $\rho_{max.}$ are more pronounced although they are still within the same order of magnitude. The three dielectric materials have fewer fluctuations in $\rho_{max.}$ which has an upward trend to longer wavelengths as the ratio of n/k increases; $\rho_{max.}$ of glass reaching a value of approximately 160 at 2000 Å. These four materials are sufficiently absorbing over the wavelength range shown so that films a few hundred Ångstroms thick are opaque.

Other metals such as Al, Mg, Ge and Si have optical properties that change character completely in the XUV; from a highly reflecting metallic character to that of a dielectric. Al [4] gives a good example of the general optical behavior of this group. It has a critical wavelength, λ_c, at approximately 840 Å due to collective oscillations of its valence electrons. To longer wavelengths, the reflectance is high and n/k is less than unity with a minimum value at about 1500 Å. At λ_c, n/k = 1.0 and for shorter wavelengths, at least to the L_{12} x-ray edge at 170 Å, the reflectance is low and n/k is greater than unity. Thus, for a semi-infinitely thick layer of Al, $\rho_{max.}$ is slightly larger than unity for $\lambda>\lambda_c$, a situation which is not changed for thicknesses as small as 1000 Å because of the large value of k. For $\lambda<\lambda_c$, $\rho_{max.}$ is continually increasing, reaching a value in excess of 10^4 at 300 Å. Because of the small value for k, however, the penetration depth of XUV radiation is large enough so that with films of practical thickness, 600 Å to 6000 Å, interference between the waves reflected from the front and back surfaces occurs.[5] Under these conditions the value of $\rho_{max.}$ cannot be calculated using the Generalized Fresnel Reflection Coefficients since multiple reflections must be taken into account.

The presence of an oxide layer on Al causes $\rho_{max.}$ to increase slightly for $\lambda>\lambda_c$, however, it is less than 2 from 1300 Å to 850 Å. At $\lambda<\lambda_c$, where Al is semi-transparent, and for Al thicknesses less than 1μ, large values of both ρ and 1/ρ are possible due to interference although reflectances are generally low. For example, at 600 Å, a reflector consisting of a glass substrate. 1000 Å of Al and 30 Å of Al_2O_3 has $1/\rho_{max.}$ = 736 with

$R_p = 1.4\%$, while for the same reflector at 500 Å, $\rho_{max.} = 182$ with $R_s = 28.0\%$. With respect to angle of incidence, the peak for $1/\rho_{max.}$ is approximately 0.1° wide at the half value points while that for $\rho_{max.}$ is about 2° wide.

Other substances may have optical properties more suitable than Al_2O_3 for enhancing the polarization of Al reflectors. A trial calculation, at 640 Å, was made for a reflector consisting of a glass substrate, 1000 Å of Al and 100 Å of Au. This particular wavelength was chosen because Au has a maximum in its index of refraction; $n = 1.157$.[6] The results are shown in Fig. 3 and compared with a similar calculation where Al_2O_3 was substituted for Au. For Au, $\rho_{max.}$ is approximately 35 and R_s about 30%, while for Al_2O_3, $\rho_{max.}$ is approximately 20 and R_s about 30%. Both peaks are approximately 10° wide at the half value points.

A practical application of polarization by reflection has been made by Rabinovitch, Canfield, and Madden [7]. Their device is an analyzer that makes use of a property of reflectors, first pointed out by Abeles [8], that at 45° angle of incidence, $R_p = (R_s)^2$, independent of n and k, providing no interference effects are present. The experimental arrangement is shown in Fig. 4 as used to measure the polarization of radiation emerging from a monochromator. The mirror is set for measurement at 45° angle of incidence and an arbitrarily chosen zero azimuth. If the reflectometer can be rotated in azimuth around the axis of the emergent beam and reflectance measurements made at two azimuthal angles 90° apart, the polarization in the beam can be calculated using the formula:

$$\frac{I_1}{I_2} = \frac{R_0(-.5+(.25+2R)^{1/2}) - R_{90}}{R_{90}(-.5+(.25+2R)^{1/2}) - R_0}$$

where the subscripts 0 and 90 refer to the two azimuth angles 90° apart and R is the arithmetic average of R_0 and R_{90}.

If the percent change in reflectance due to polarization of the incident beam is taken as a measure of the sensitivity of the analyzer, it is a simple calculation to show that the sensitivity is dependent on n and k, and that maximum sensitivity occurs when n and k are approximately 1.3 and 0.3 respectively. The calculations were limited to maximum values for n and k of 2.3 and 3.3, respectively, which includes most values found in the XUV. For this pair of n and k, however, the reflectance for unpolarized radiation is only about 10%, so that while the percent change is maximum, the advantage may be cancelled by inaccuracies in measuring the reflectance.

2. Transmission

Over the wavelength range where non-absorbing crystals are available, transmitting polarizers can be made in the classical form of a pile-of-plates, set at the Brewster angle. Walker [9] has reported the properties of such a polarizer, made from cleaved LiF plates held approximately at the Brewster angle. In the wavelength range from 1800 Å to 1216 Å, the index, and hence the Brewster angle, does not change rapidly, therefore the polarizer can be used over a fairly wide wavelength range without adjustment. Walker obtained intensity ratios of the parallel component of the perpendicular component, $1/\rho$, ranging from 3 at 1600 Å to 10 at 1216 Å with four plates. The transmittance for the p-component was 20% at 1600 Å and 4% at 1216 Å.

In the wavelength region below 1050 Å quite a few metals have transmission windows.[10] For example, Al, Ge, Si, Sn, Bi, etc. to name a few. At least two metals, Mg and Pb, transmit to wavelengths longer than 1050 Å. Most of these materials can be made into unbacked films ranging in thickness from a few hundred Angstroms to thousands of Angstroms. Because of their small values of k, n/k is large and their optical properties resemble those of a dielectric, hence in principle, it is possible to use them in the form of unbacked films held approximately at the Brewster angle in a variation of the pile-of-plates polarizer mentioned above.

The properties of such a polarizer will be illustrated by calculations for Al. The value of $1/\rho$ was calculated as a function of angle of incidence for wavelengths ranging from 300 Å to 800 Å and the results are shown in Fig 5. The effect of the oxide layer was not included in this calculation. As a transmitting polarizer, Al is rather poor; the maximum value of $1/\rho$ occurs at about 700 Å and is less than 3, while T_p is approximately 20%. The effect of the oxide layer was included in a calculation at 584 Å and in Fig. 6 are shown the transmittance and polarization of Al films of several thicknesses with a 30 Å thick oxide layer on either side. There is practically no change in $1/\rho$ between this wavelength and 600 Å in the preceeding figure. Increasing the thickness of the Al layer causes a decrease in transmittance, as would be expected, makes $1/P$ more sensitive to angle, and introduces subsidiary maxima in $1/\rho$. The dashed curves for $(1/\rho)^2$ and $(T_p)^2$ are included to show the effect of using two separate films in tandem.

An attempt was made to measure the degree of polarization due to an unbacked film of Al, 1000 Å thick, using another film as the analyzer. A small effect was found but, because the low radiation intensity caused the signal-to-noise ratio in the detecting equipment to be low, the results were inconclusive. Somewhat more successful measurements were made by replacing the analyzer film with the reflecting analyzer described above, and the following results were obtained: at 555 Å, $1/\rho \approx 1.5$, and at 620 Å, $1/\rho \approx 3.4$. The disagreement of these results with the calculations can be attributed to two causes; first, inaccuracies in measurements, about $\pm$ 30%, due to low signal-to-noise ratios, and second, the possibility that the optical constants of the natural oxide are not the same as the anodically formed oxide.

At longer wavelengths, the increased contrast between the optical constants of Al and Al_2O_3 causes $1/\rho$ to increase. For example, the calculated transmittances of Al, with and without oxide layers, at 640 Å, are shown in the left hand and center panel of the figure. With no oxide present, $1/\rho$ is approximately 2.5, however, the presence of the oxide increases the ratio to 7.

The right hand panel in Fig. 7 shows the effect of substituting 100 Å of Au for the two oxide layers on an unbacked film of Al 500 Å thick. The value of $1/\rho$ has been increased to approximately 15 while T_p has been reduced to 2%. Apparently gains in $1/\rho$ will be off-set by the reduction in transmittance. Such a film may be useful in photographic applications, or in photoelectric work when the radiations intensities are high.

III. CONCLUSIONS

The experimental work of Cardona in obtaining polarized radiation by reflection from a LiF surface shows that it is possible to obtain almost completely polarized radiation to wavelengths as short as 1200 Å. At present, very little experimental work has been done to shorter wavelengths but the calculations indicate that it is possible to construct reflecting polarizers with efficiencies ranging from a few percent to 30% or more, and whose degree of polarization ranges from slightly greater than unity to 10^3 or more. However, an extremely complicated mechanical arrangement that must be operated through the wall of a vacuum system may prove a considerable deterrent to their widespread use.

Walker has made a transmission polarizer by using a pile of LiF plates that can be used from 1600 Å to 1200 Å although it is not too efficient nor is its degree of polarization very large. The calculations presented above and some preliminary experimental results show that such transmitting polarizers are possible at shorter wavelengths using unbacked metal films, but not with the efficiency or degree of polarization that can be obtained with reflecting polarizers. On the other hand, the mechanical arrangement required for their use is very simple and may outweigh the disadvantages of their low efficiency and degree of polarization.

Acknowledgments.

The author wishes to express his gratitude to Messrs. K. Rabinovitch, L.R.Canfield, and R. P. Madden for information concerning the use of a reflecting surface as an analyzer, to W. C. Walker and M. Cardona for permission to use their results prior to publication, and to D. W. Angel for the unbacked films of aluminum.

References:

1. M. Cardona: Solid State Communications 1, 109, 1963, and private communication.

2. J. C. Phillips: Phys. Rev. 133, A452, 1964.

3. T. Sasaki and H. Fukutani: Japan. J. Appl. Phys. 3, 125, 1964.

4. W. R. Hunter: J. de Physique 25, 154, 1964,

5. W. R. Hunter: Optica Acta 9, 255, 1962.

6. L. R. Canfield, G. Hass, and W. R. Hunter: J. de Physique 25, 124, 1964.

7. K. Rabinovitch, L. R. Canfield, and R. P. Madden: To be published in Appl. Optics.

8. F. Abeles: Compt. rend. 230, 1942, 1950.

9. W. C. Walker: To be published in Appl. Optics.

10. W. R. Hunter and R. Tousey: J. de Physique 25, 148, 1964.

Captions:

Fig. 1. Calculated ρ_{max} and R_s as a function of n for $k = 0.1, 0.5$, and 1.3 .

Fig. 2. Calculated ρ_{max} and R_s as a function of wavelength for glass, Au, Zns, and Al_2O_3 .

Fig. 3. Calculated ρ and reflectance of Al on glass with Au and Al_2O_3 coatings.
$t_{Al_2O_3} = 30$ Å, $t_{Au} = 100$ A, $\lambda = 640$ Å .

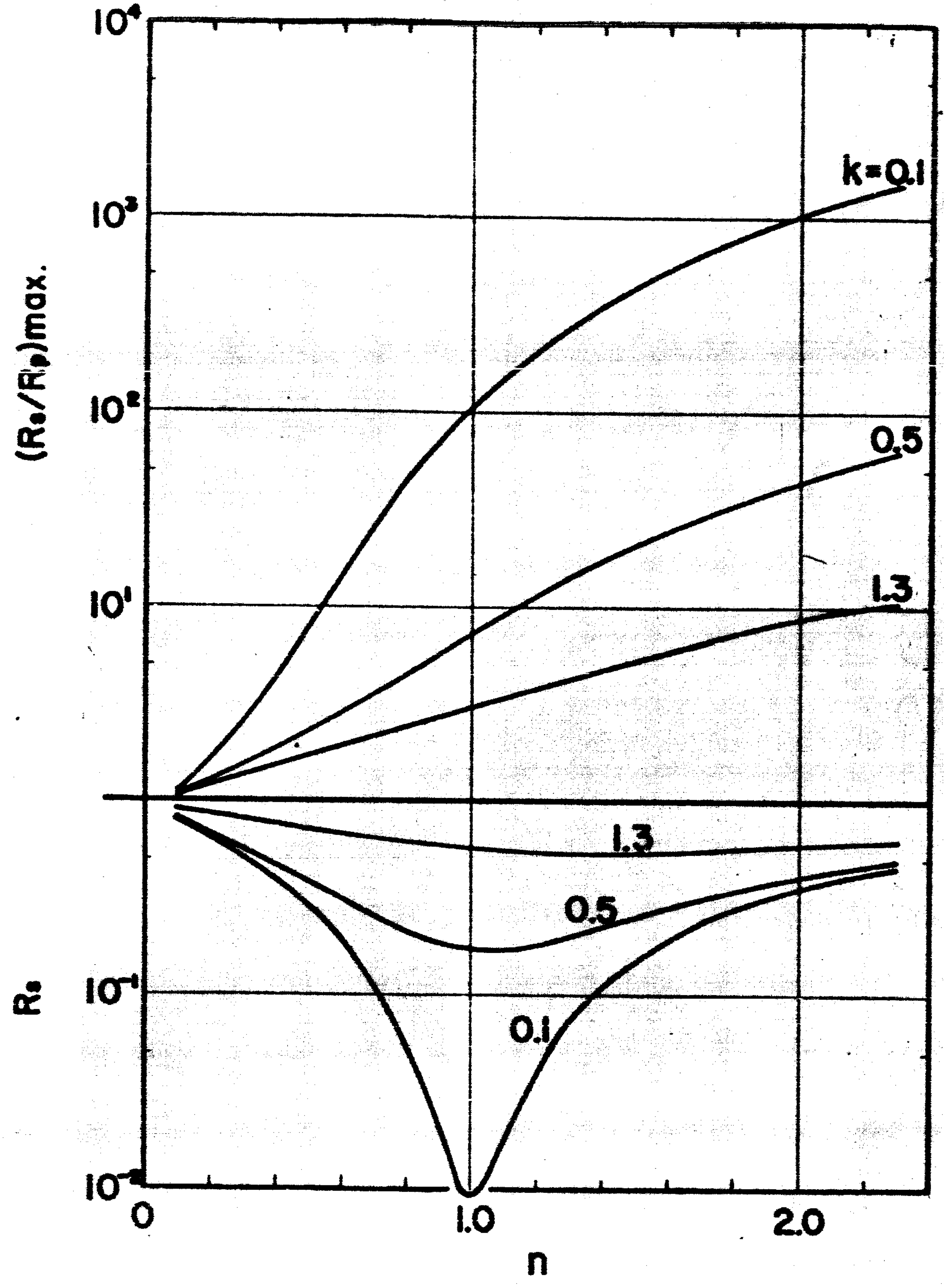
Fig. 4. Reflecting analyzer for measuring the polarization in the emerging beam of a monochromator.

Fig. 5. Calculated $1/\rho$ and transmittance of unbacked Al films as a function of angle of incidence at wavelengths shorter than the critical wavelength.
$t_{Al_2O_3} = 0$, $t_{Al} = 1000$ Å .

Fig. 6. Calculated $1/\rho$ and transmittance of unbacked Al films with 30 Å of oxide on each side at 584 Å. The dashed curves for $(1/\rho)^2$ and $(T_p)^2$ are included to show the effect of using two separate films in tandem.

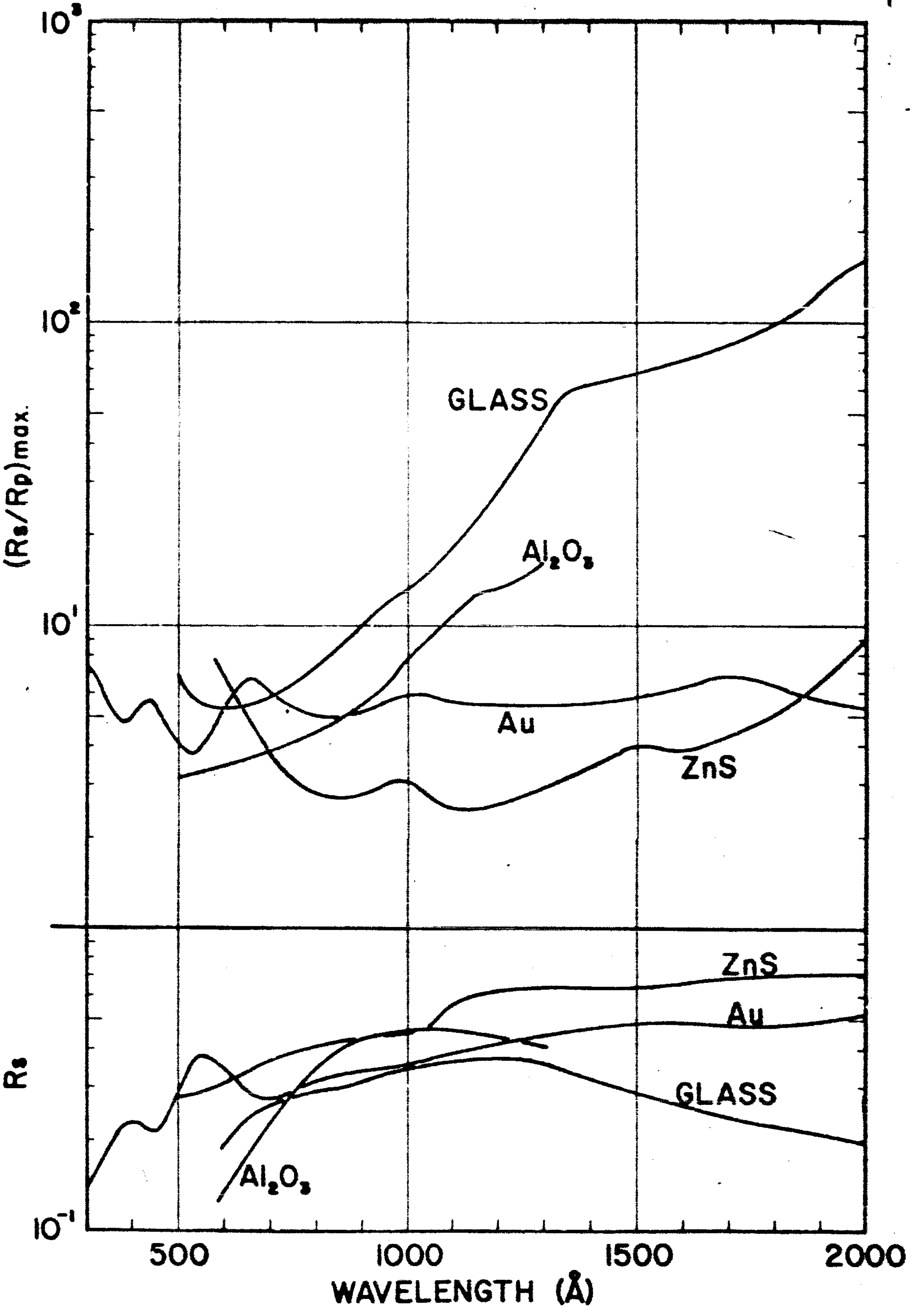
Fig. 7. Calculated $1/\rho$ and transmittance of unbacked films of Al with Al_2O_3 and Au coatings on each side of the Al.

$t_{Al_2O_3} = 30$ Å, $t_{Au} = 100$ Å, $\lambda = 640$ Å.



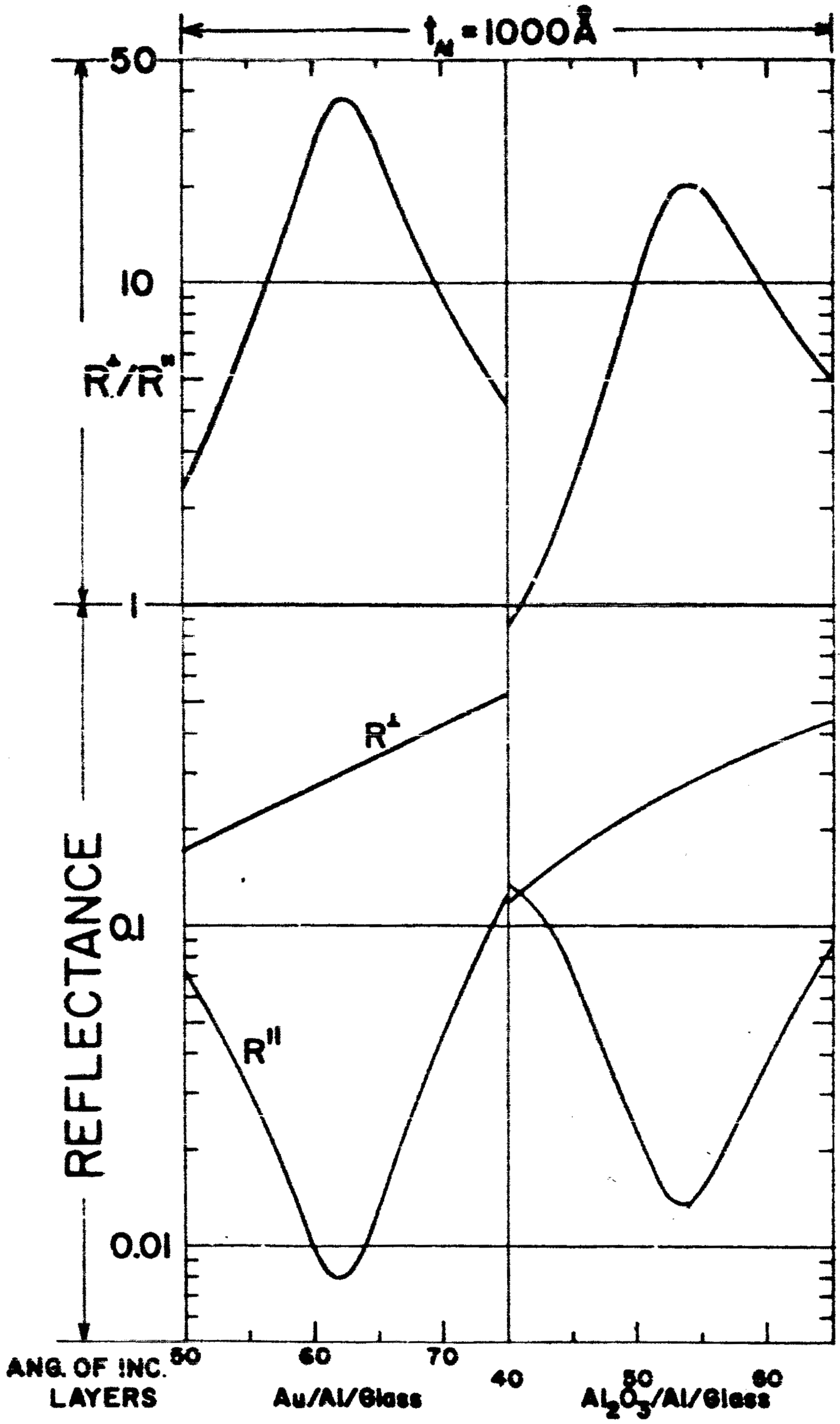
(R_s/R_p)max. & R_s AS A FUNCTION OF n FOR THREE VALUES OF k.

FIG. 1



(Rs/Rp)max. & Rs CALCULATED FOR GLASS, Al_2O_3, Au & ZnS

FIG. 2



CALCULATED REFLECTANCE OF Al ON GLASS WITH Au & Al_2O_3 COATINGS. $t_{Al_2O_3} = 30Å$, $t_{Au} = 100Å$, $\lambda = 640Å$

FIG. 3

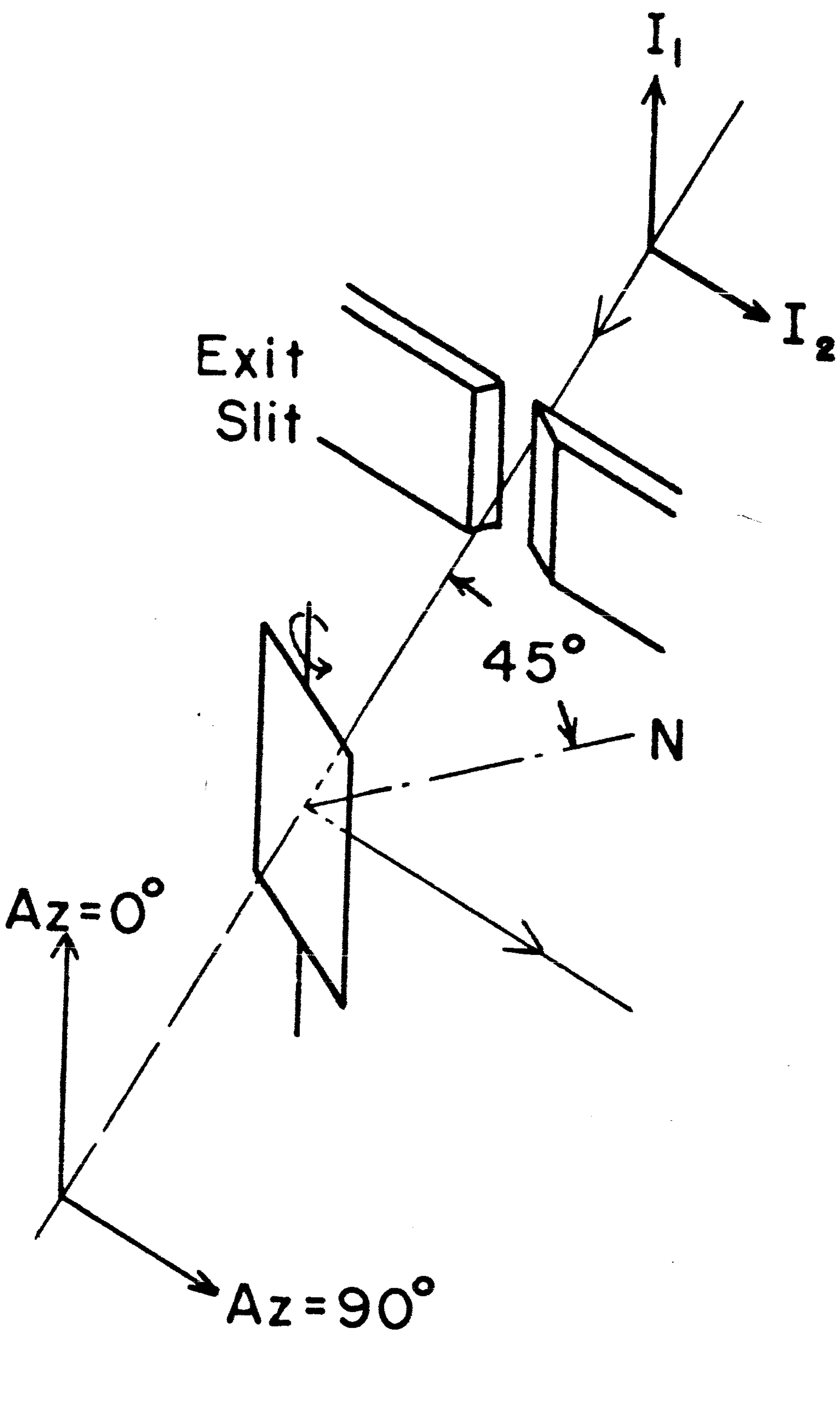
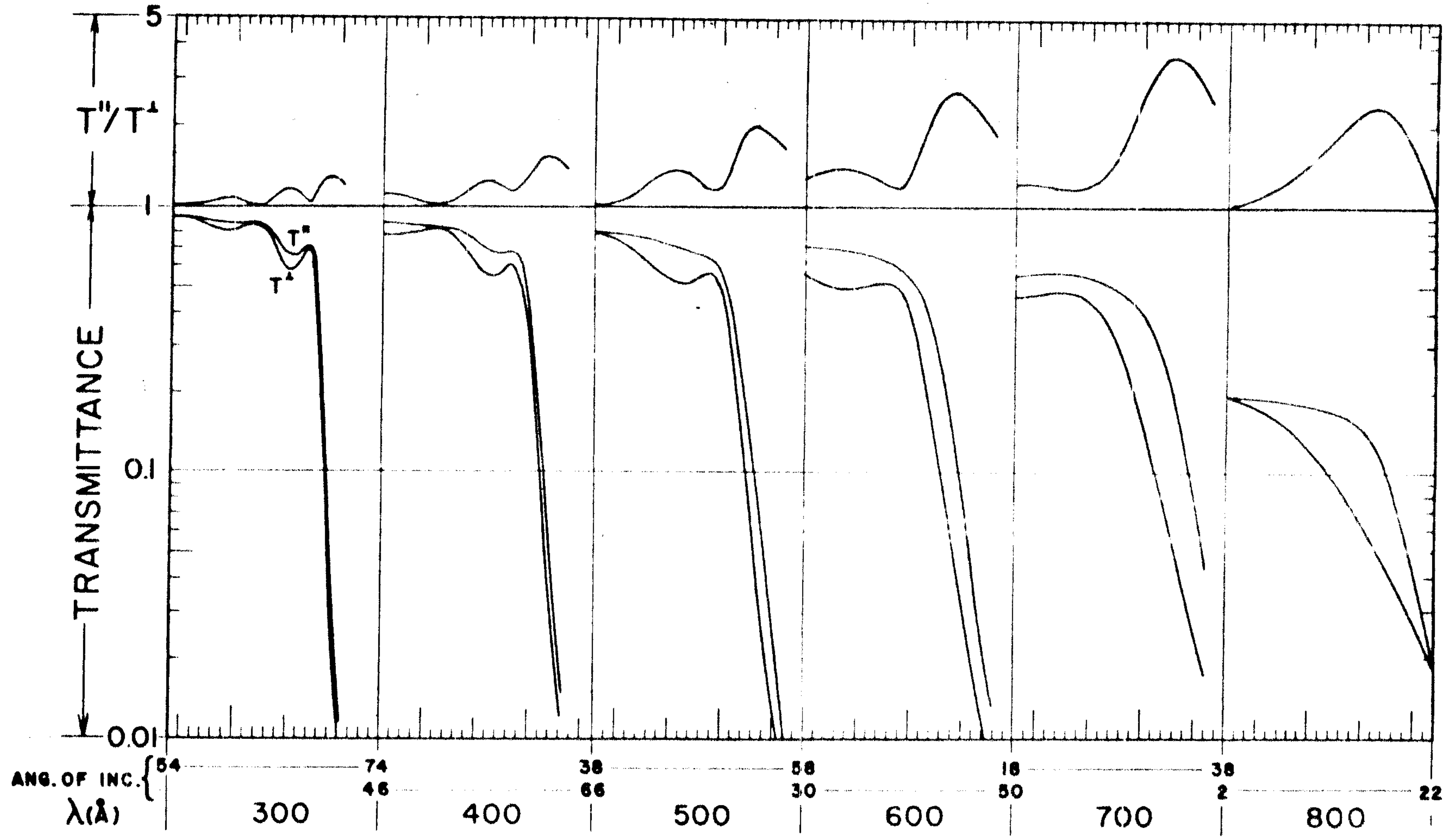
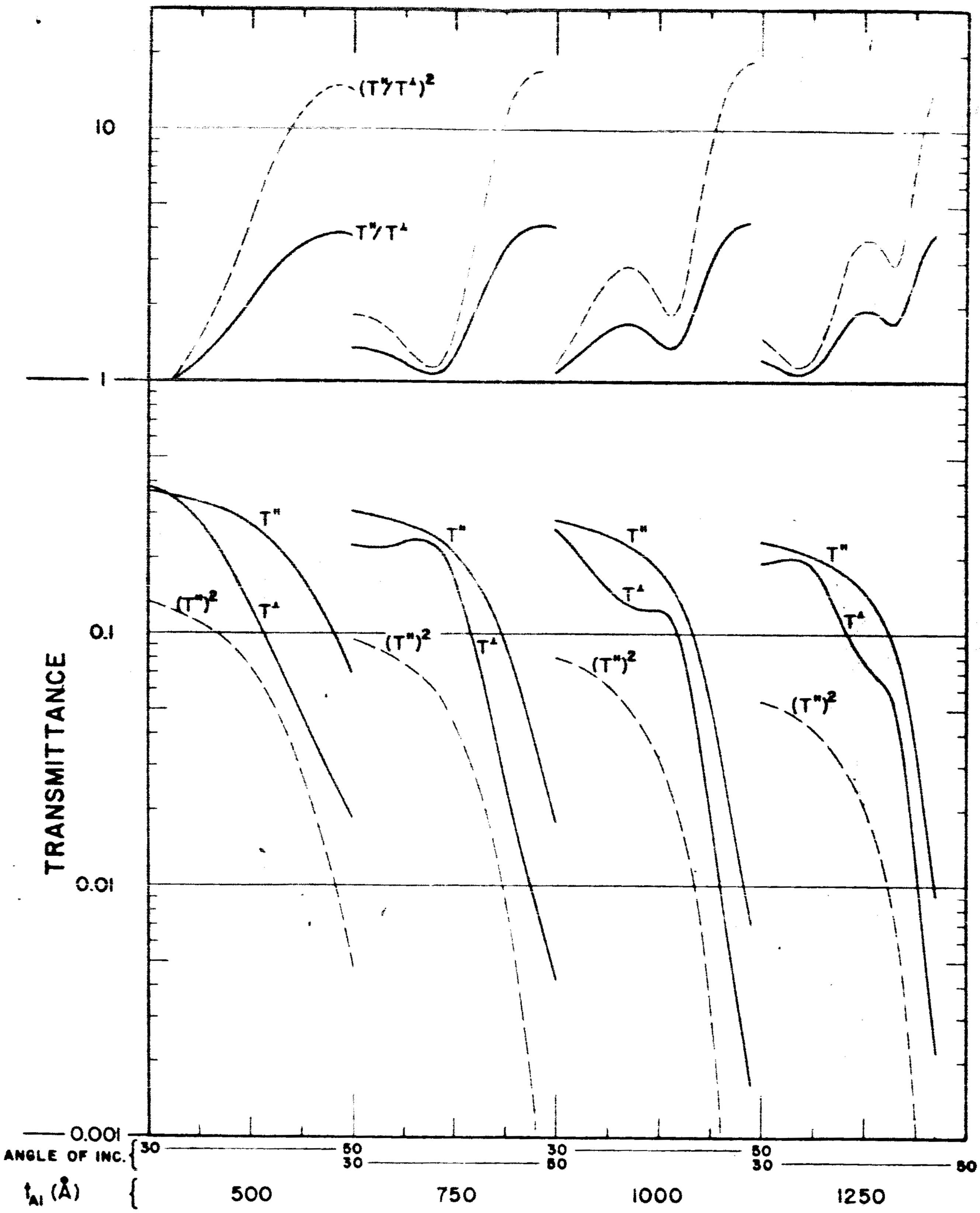


FIG. 4



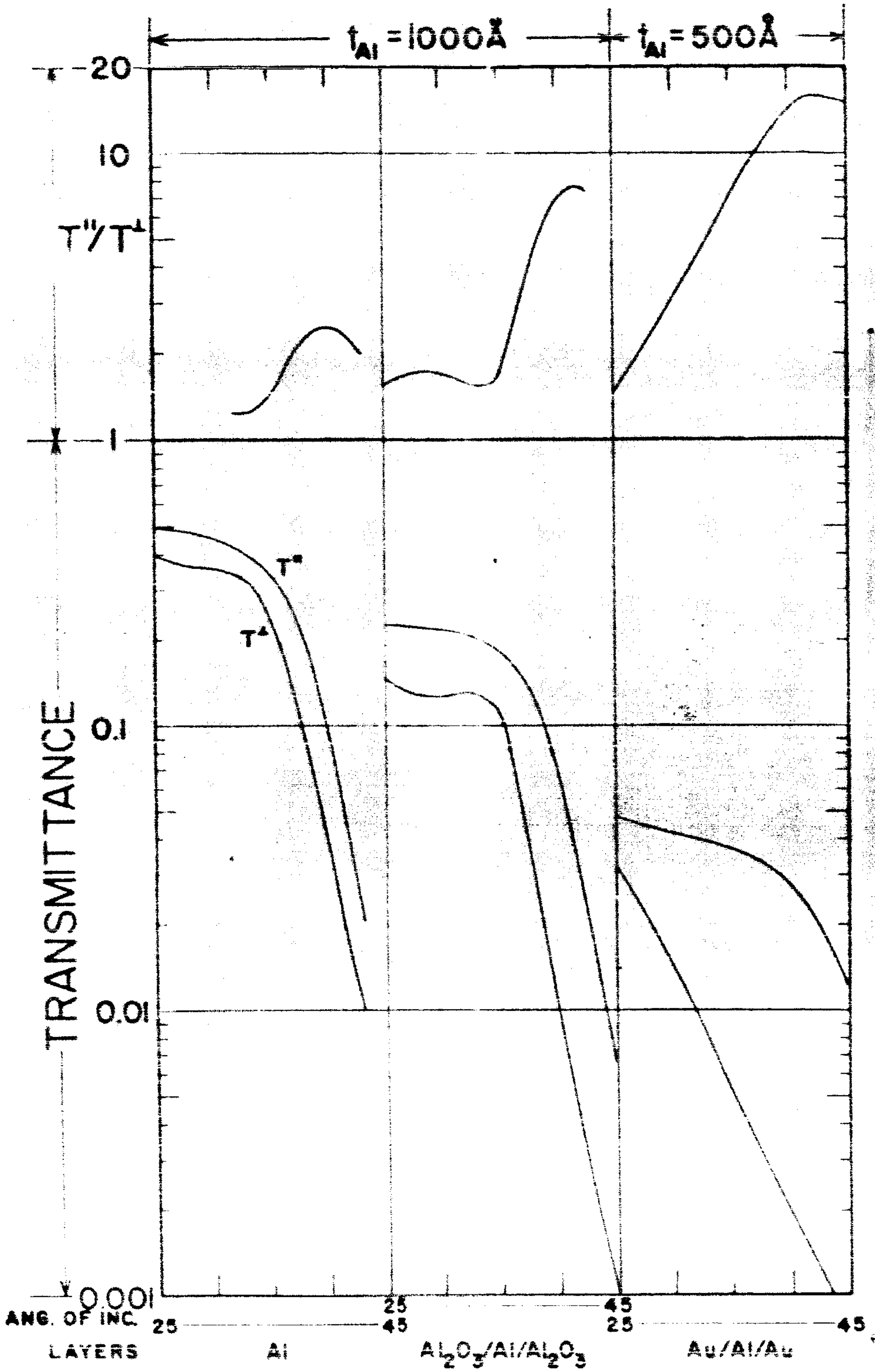
TRANSMITTANCE OF UNBACKED ALUMINUM FILMS AS A FUNCTION OF ANGLE OF INCIDENCE AT WAVELENGTHS SHORTER THAN THE CRITICAL WAVELENGTH. $t_{Al_2O_3} = 0$, $t_{Al} = 1000$ Å.

FIG. 5



CALCULATED TRANSMITTANCE OF UNBACKED Al FILMS WITH 30Å OF OXIDE ON EACH SIDE AT 584Å.

Fig. 6



CALCULATED TRANSMITTANCE OF UNBACKED Al FILMS WITH Al_2O_3 & Au COATINGS ON BOTH SIDES OF THE Al. $t_{Al_2O_3} = 30Å$, $t_{Au} = 100Å$. $\lambda = 640Å$

Fig 7